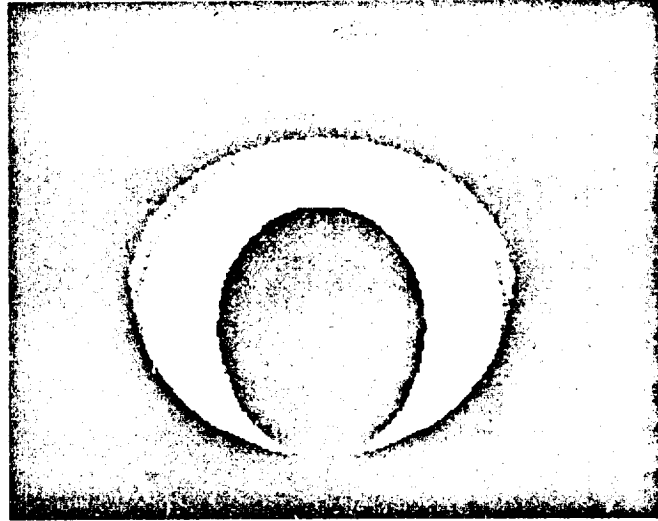
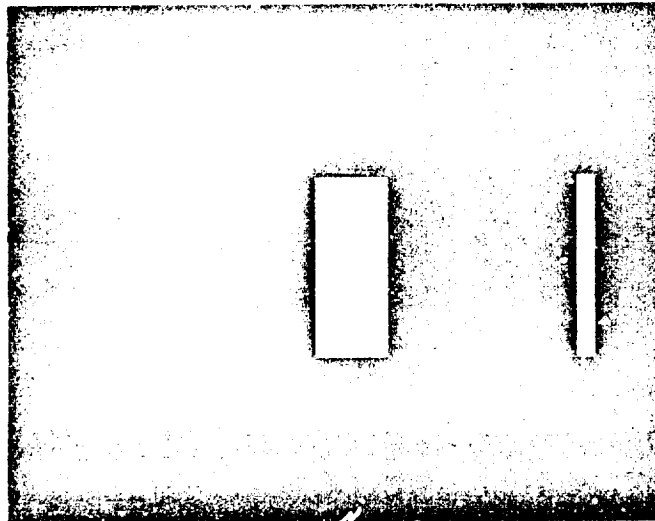
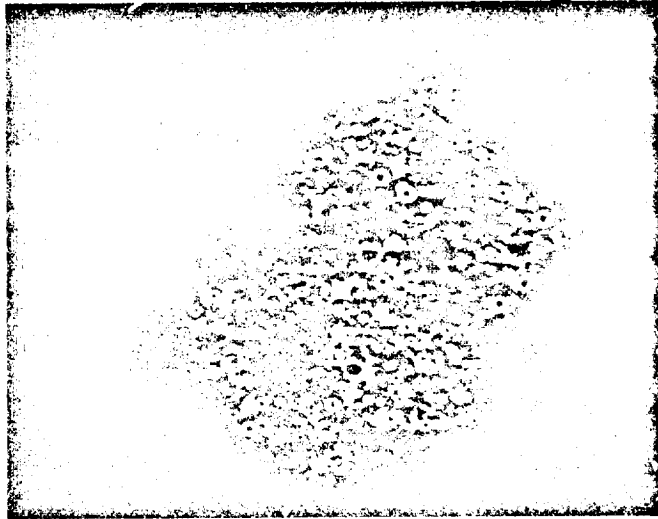
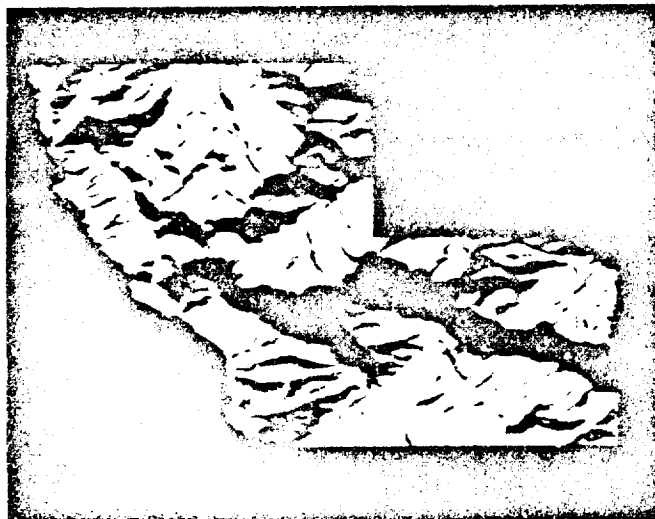


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*Modeling Topographic Influences on  
Solar Radiation: A Manual for the  
SOLARFLUX Model*

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**Cover:** These four maps of daily incoming solar radiation demonstrate that SOLARFLUX can be used to model solar radiation for topographic surfaces at different spatial scales, ranging from landscape scales to local levels. The upper-left map shows clear-sky direct solar radiation on the equinox for the University of California Big Creek Reserve, the upper-right map shows clear-sky direct solar radiation on the summer solstice for a pinon-juniper woodland stand at Los Alamos National Environmental Research Park, the lower-left map shows clear-sky direct solar radiation on the summer solstice for a series of experimental plots that test the influence of slope on waste site design, and the lower-right map shows spatial variability of solar radiation on the summer solstice for a simulated treefall gap. See Chapter III for further details.

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*Modeling Topographic Influences on  
Solar Radiation: A Manual for the  
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## PREFACE

SOLARFLUX is a public domain computer program developed in my research laboratory for modeling effects of topography on incoming solar radiation. The conception of SOLARFLUX has roots that go back more than a decade, to the early 1980s when I first began grappling with concepts of how to model the complexities of solar radiation as it influences the ecology of tropical rainforests. Since that time, my thinking about geometric models of solar radiation has encompassed a wide range of systems, both natural and human made, and a wide range of temporal and spatial scales. For me, the development of SOLARFLUX is part of a natural progression from a focus on geometric models of solar radiation for point locations to a focus on geometric solar radiation models that integrate over areas. These areas may range in scale from meters to thousands of kilometers — at local, landscape, or regional scales.

In a certain sense, I started by looking at the world upside down, from the perspective of a tree growing in the understory of a mature tropical rainforest. In the rainforest, light is a limiting resource, and the geometry of openings in the forest canopy determines how much light is available for growth by plants growing in the understory. From 1982 to 1989 I worked on developing CANOPY, a program for digital image analysis of hemispherical (fisheye) canopy photography. In essence, CANOPY can be used to quantify the pattern of sky obstruction and openings as seen from a given location looking upward, and to calculate the level of radiation that would penetrate to the location from unobstructed sky directions. The pattern of canopy openings, or gap fractions, can also be used to model the architecture of the canopy above, including such ecologically important characteristics as leaf area index and leaf angle distribution. CANOPY was written as a general program that could be used to analyze hemispherical imagery at any latitude, and not just in forest ecosystems. CANOPY can be used equally well to calculate the influence of mountains, buildings, or trees on incoming solar radiation. But CANOPY is limited to the perspective of looking upward from a given location. CANOPY and SOLARFLUX literally view the world from opposite directions: CANOPY looks upward from a point location, while SOLARFLUX looks downward on a topographic surface.

SOLARFLUX is not as different from CANOPY as it might appear upon first inspection. True, SOLARFLUX uses a different source of input than CANOPY — SOLARFLUX starts with a topographic surface, generally specified as an array of elevation values, while CANOPY starts with a hemispherical image that is turned into an array of sky directions that are then classified as either obstructed or open. And true, the outputs are different in presentation — SOLARFLUX produces a map of solar radiation values for a topographic surface, while CANOPY produces tables of solar radiation indices for a given location. But, in both input and output, the two programs are actually quite similar, and in some aspects identical. Both start with a representation of geometry that influences incoming solar radiation. And both end with calculations of how this geometry influences solar radiation. In fact, the core calculating algorithm of SOLARFLUX is the same as the algorithm used by CANOPY. SOLARFLUX progressively calculates the influence of sky obstruction and surface orientation for each location on a topographic surface. This is comparable to acquiring and analyzing an array of hemispherical photographs corresponding to each location on the surface. Thus, SOLARFLUX is a tool that integrates over space and time based upon relatively readily available information, namely specification of a topographic surface.

SOLARFLUX was my conception. But its realization is the result of efforts by many people, including various student assistants in my research laboratory and several key collaborators. In particular, I hired William Hetrick, a talented computer engineering undergraduate student at the University of Kansas, as a research assistant to develop the

software code of SOLARFLUX. He did what I no longer have time for in my capacity as an assistant professor — he spent long hours writing and debugging the computer code in SOLARFLUX. In the spirit of academic endeavor, the program development became more than a job in which William Hetrick turned my ideas into well written code, but rather he contributed substantial ideas concerning design and implementation. In addition, Shawn Saving, Jue Wang, and Xiofei Tang, graduate research assistants in my laboratory at the University of Kansas, contributed substantially to testing of SOLARFLUX. Throughout the project, Stuart Weiss of the Stanford Center for Conservation Biology, offered constructive criticism, encouragement, and unending enthusiasm. As a kindred spirit, he offered insights into profound ecological and evolutionary implications of topographic modification of solar radiation. In the course of the project, I began collaboration with Ralph Dubayah of the University of Maryland Department of Geography, who has independently developed a topographic solar radiation model for application in remote sensing. Together, we have been working to produce a synthesis of the state of knowledge of such geometrically based solar radiation models. Our collaboration has contributed greatly to increasing both the depth and breadth of my understanding of the subject.

This manual serves as a technical reference to the program SOLARFLUX. More than that, it serves to show directions for developing more sophisticated and complete geometric models of solar radiation.

Paul M. Rich, 15 August 1995  
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and Kansas Biological Survey,  
University of Kansas



# MODELING TOPOGRAPHIC INFLUENCES ON SOLAR RADIATION: A MANUAL FOR THE SOLARFLUX MODEL

by

Paul M. Rich, William A. Hetrick, and Shawn C. Saving

## ABSTRACT

SOLARFLUX is a geographical information system (GIS) based computer program (running under ARC/INFO and GRID) that models incoming solar radiation based on surface orientation (slope and aspect), solar angle (azimuth and zenith) as it shifts over time, shadows caused by topographic features, and atmospheric conditions. A convenient user interface allows specification of program parameters including latitude, time interval for simulation, file name of a topographic surface, atmospheric conditions (transmittivity), and file names for output. The user specifies a topographic surface as an array of elevation values (GRID). SOLARFLUX generates five basic types of output: 1) total direct radiation, 2) duration of direct sunlight, 3) total diffuse radiation, 4) skyview factor, and 5) hemispherical viewsheds of sky obstruction for specified surface locations. This manual serves as the comprehensive guide to SOLARFLUX. Included are discussions on modeling insolation on complex surfaces, our theoretical approach, program setup and operation, and a set of applications illustrating characteristics of topographic insolation modeling.

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## CHAPTER 1: INTRODUCTION

### OVERVIEW

#### Motivation: Modeling Influences of Topography on Incoming Solar Radiation

The effects of solar radiation are pervasive. Solar radiation is the primary source of energy that drives earth system processes, such as weather patterns and rates of primary production by green plants. Topography is a major factor that determines the amount of solar radiation reaching any particular location on the Earth's surface. These topographic influences result from variability in elevation, surface orientation (slope and aspect), and shadows caused by topographic features. Models of the spatial and temporal patterns of incoming solar radiation (insolation), as influenced by topography, are of interest to a diverse community of scientists, engineers, planners, and resource managers. While the physical behavior of solar radiation is well understood (Gates 1980, Lunde 1980, Monteith and Unsworth 1990), it has not previously been practical to model incoming solar radiation for complex topographic surfaces because of intensive calculation requirements. Appropriate solar radiation models must account for changes in solar angle with time, atmospheric effects, and topographic influences of elevation, surface orientation, and shadows. The detailed geometric analyses necessary to account for these topographic influences are only now becoming practical due to advances in both computer hardware and software technology (Dozier 1980, 1989, Brown 1992, Dubayah 1992, Dubayah *et al.* 1990, Hetrick *et al.* 1993a, 1993b, Dubayah and Rich 1995). Herein, we describe our

approach to develop software, based on a geographical information system (GIS) platform, that takes advantage of new generation computers to model insolation on complex topographic surfaces.

### **Purpose and Organization of this Manual**

This manual serves two basic purposes. First, it serves as a comprehensive guide to SOLARFLUX, a GIS-based solar radiation program. Second, it serves to showcase a series of SOLARFLUX applications at a variety of spatial scales. This manual is not meant to provide a comprehensive treatment of the theory and design of SOLARFLUX, since that has been published elsewhere. A detailed treatment concerning the theoretical basis of topographic solar radiation models is provided in Dubayah and Rich (1995), while Hetrick *et al.* (1993a, 1993b) provides background concerning the theory and conceptual basis for the SOLARFLUX model.

This chapter provides a general introduction and overview of topographic solar radiation modeling, background concerning solar radiation models and their applications, and an introduction to the program SOLARFLUX. Chapter II presents a series of applications using SOLARFLUX to calculate incoming solar radiation for topographic surfaces at various spatial scales; and Chapter III details the operation of SOLARFLUX, including software setup, input and output, and program operation.

## **BACKGROUND**

### **Solar Radiation Models**

Incoming solar radiation is variable at all temporal and spatial scales, but this variation is generally understandable and subject to quantitative modeling. Temporal variation in global insolation is a function of time of year and cloud cover, and drives seasonal cycles (Lieth 1973). Because insolation is poorly sampled in weather station networks, models have been developed to estimate insolation based on first principles (Gates 1980, Lunde 1980, Monteith and Unsworth 1990, Dubayah and Rich 1995), and many approaches incorporate standard weather data (Nicks and Harp 1980, Bristow and Campbell 1984, 1985, Becker and Weingarten 1991). Spatial and temporal variation in site-specific insolation at both local and landscape levels is predictable from basic geometric principles, and this variation is a major cause of climatic differentiation across local topography (Geiger 1965, Rich and Weiss 1991, Galo *et al.* 1992, Dubayah 1992, Saving *et al.* 1993, Dubayah and Rich 1995). Insolation is a function of latitude, day of year, time of day, slope and aspect of the receiving surface, and horizon obstruction. Numerous algorithms and computer programs exist for geometric insolation calculations (*e.g.* Swift and Knoerr 1973, Lunde 1980, Nunez 1980, Revfeim 1982, Dozier and Frew 1990). Integration of spatio-temporal insolation models into a GIS-based model provides powerful analytical tools for numerous disciplines, from ecology and hydrology to architecture and urban planning.

### **Applications**

Spatially based insolation models offer powerful analytical capabilities of value to numerous disciplines. Topographic effects on insolation and its effect on ecology has been the subject of literally hundreds of studies (see review in Hetrick *et al.* 1993a). In ecology, solar radiation models can be applied at individual, community, ecosystem, and landscape levels. For example, local light conditions influence growth of individual plants (Pearcy 1983); heterogeneity of microclimate influences distribution of different species in a

community (Weiss *et al.* 1988, 1991, Weiss and Murphy 1990, Rich and Weiss 1991, Rich *et al.* 1992); solar radiation limits ecosystem productivity and influences energy and water balances (Lin *et al.* 1992); and quantifying solar radiation flux is essential for evaluating climate fluctuations at the landscape level (Running 1984, Running *et al.* 1987, Pacala and Hurtt 1993, Schimel 1993). In remote sensing, coupling insolation models with vegetation canopy reflectance models (Goel 1988, Hail *et al.* 1991, Schaaf and Strahler 1993) and landscape topographic patterns (Dubayah *et al.* 1989, 1990, Dubayah 1992) can enhance the interpretation of reflectance measurements. Insolation models can also be used in architecture, design, and urban planning to simulate various design and management options. For example, different building sites can be evaluated on simulated landscapes. Similarly, changes in landscape features (e.g. addition or removal of trees or structures) can be evaluated. Because simulation of incident radiation on complex surfaces is scale independent, except at very local scales where penumbral effects become important (Smith *et al.* 1989), spatially based insolation models have broad applications in both theoretical and applied problems at many scales.

### **The Program SOLARFLUX**

SOLARFLUX is a GIS-based program for modeling incoming solar radiation based on surface orientation, solar angle, shadowing due to topographic features, and atmospheric attenuation. Surface topography is defined in a raster-based array (grid) of elevation data. Global location of the surface (longitude and latitude) and time interval for calculation are specified by the user. The result is a grid of insolation values for each surface location during the specified time interval. SOLARFLUX calculates five basic types of output: 1) total direct radiation, 2) duration of direct sunlight, 3) total diffuse radiation, 4) skyview factor (proportion of unobscured sky), and 5) hemispherical viewsheds of sky obstruction for specified surface locations. Our approach is basically geometrical in nature and can incorporate either empirical or theoretical distributions of incoming solar radiation.

## **FUNDAMENTAL PRINCIPLES**

### **Incoming Solar Radiation**

Solar radiation refers to electromagnetic radiation originating in thermonuclear reactions on the sun. Because of the large distances involved, and the relatively small size of the Earth as compared with the sun, only a very small fraction of the energy emitted reaches the Earth. Solar radiation is transmitted directly to the Earth through a virtual vacuum. The amount of solar radiation reaching the Earth is relatively constant, and can be described by a single value of  $1353 \text{ W/m}^2$ , known as the solar constant,  $S_0$ , adjusted by a factor to account for the elliptical orbit of the Earth about the sun. The gases and particles of the Earth's atmosphere modifies incoming solar radiation by processes of scattering, absorption, and reradiation. Solar radiation is further modified at the Earth's surface by topography and local surface characteristics. For any given location at the Earth's surface, the incoming solar radiation, or insolation, consists of three components: 1) direct radiation, which is transmitted unimpeded along the path between the sun and the Earth; 2) diffuse radiation, which results from atmospheric scattering from any sky direction; and 3) reflected radiation, which consists of direct and diffuse radiation that is reflected off surrounding terrain features (Figure 1). Insolation is calculated by integrating direct, diffuse, and reflected radiation components over a specified time interval.

## Topographic Effects

Topography has two important effects on the insolation at a given location: 1) surface orientation determines the angle of incidence of direct, diffuse, and reflected radiation; 2) sky obstruction by surrounding topography limits the directions from which direct and diffuse radiation can originate. In the case of direct radiation, sky obstruction by topographic features along the path of the sun leads to shadows and times when no direct radiation reaches the location. Sky obstruction in any sky direction will limit the amount of diffuse solar radiation reaching a given location.

The hemispherical viewshed algorithm (Rich et al. 1994) warrants further description, because it is at the heart of SOLARFLUX's skyview factor and diffuse calculations and has broad applicability for efficient geometric modeling. The algorithm, originally developed by Rich (1989, 1990) for analysis of hemispherical photography, can be generalized in the following way. First, the angular distribution of sky obstruction is specified in a hemispherical coordinate system, in which the hemisphere of sky directions is projected on a plane. Second, the sky is divided into a discrete number of sectors, corresponding to reasonably small ranges of zenith and azimuth angles, and the angular area of unobstructed sky corresponding to each sky sector is determined. Third, for each sky sector, the proportion of unobstructed sky is multiplied by the corresponding irradiance for that entire sky sector, and by a factor that provides a cosine weighting appropriate for the angle of incidence between the sky sector and the surface of interest. Finally, the resulting radiance values of all sky sectors, which now account for sky obstruction and angle of incidence, are summed to obtain total incident radiation for the location of interest. By using precalculated lookup tables of direct and diffuse irradiance values corresponding to each sky direction, calculations can be made very rapidly.

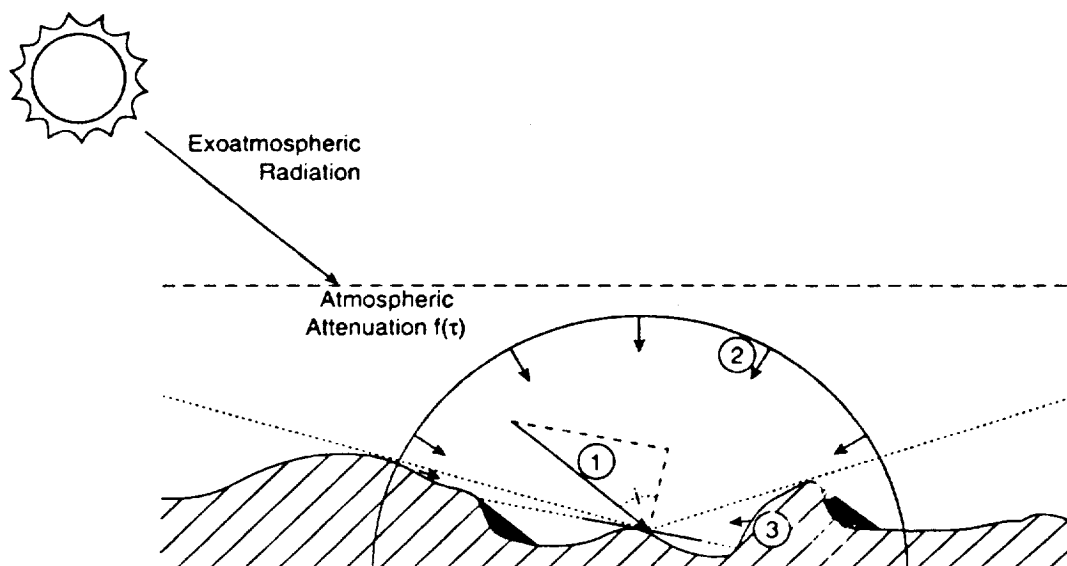


Figure 1. Incoming solar radiation (insolation) at a location on a topographic surface consists of three components: 1) direct radiation, originating from the direction of the sun; 2) diffuse radiation, originating from any sky direction as the result of scattering by atmospheric gases and particles; and 3) reflected radiation from nearby terrain. Calculations of insolation must account for atmospheric attenuation, angle of incidence of all radiation components, and sky obstruction by surrounding topographic features.

## **Calculation of Topographic Influences on Insolation**

Topographic models must account for the effects of surface orientation and sky obstruction by surrounding topographic features. Two different, but related approaches can be used to account for topographic effects on solar radiation. The first approach, applicable for direct radiation calculations, involves calculating shadow patterns, using ray tracing techniques, across a topographic surface at a series of discrete time steps and then calculating the angle of incidence of direct radiation reaching each surface location that is not in shadow for each time step. This is the approach currently used for direct insolation calculations by SOLARFLUX (Hetrick et al. 1993a, 1993b). The second approach, applicable for either direct or diffuse calculations, involves calculating hemispherical viewsheds for each surface location, wherein the geometry of sky obstruction is determined by ray tracing techniques (Rich et al. 1994). This hemispherical viewshed approach can then be used to integrate values of direct and diffuse insolation originating from non-obscured sky directions.

## **CAPABILITIES OF SOLARFLUX**

### **Total Direct Radiation**

The intercepted direct beam solar energy, total direct radiation, is calculated for each position on the surface using standard calculating formulae to determine solar angle (zenith and azimuth) and atmospheric attenuation. Atmospheric attenuation is based on a transmittivity value, the proportion of radiation that passes unimpeded through the atmosphere in a vertical direction, and the length of atmosphere traversed in non-vertical directions. Larger zenith angles lead to lower incident direct radiation due to atmospheric attenuation. Elevation effects are accounted for on surfaces with high relief by calculating changes in transmittivity as a function of elevation. The effect of surface orientation is accounted for by using a cosine correction based on the angle of incidence, i.e., the angle between the solar angle and the axis normal to the surface. For each time interval, shadow patterns are determined using the hillshade function in ARC/INFO, which assigns values of zero to locations shaded by topographic features (i.e., no direct radiation received during that time interval). The hillshade function can be disabled by the user, which makes it possible to evaluate the importance of shadows.

### **Duration of Direct Sunlight**

The total time during which a surface position receives direct beam radiation, duration of direct sunlight, is calculated by summing time intervals when surface locations are not shaded.

### **Skyview Factor**

The ratio of diffuse sky irradiance relative to that on an unobstructed horizontal surface, skyview factor (Reifsnyder 1967), is calculated for each surface location. The term skyview factor is equivalent to the "indirect site factor" with a cosine correction (ISFC) and an isometric (uniform) diffuse illuminance distribution and to the term "diffuse transmission coefficient" (Rich 1990). The current implementation of SOLARFLUX assumes an isotropic distribution of diffuse irradiance throughout the hemisphere of sky directions (see Dozier and Frew 1990). However, the hemispherical viewshed algorithm used in SOLARFLUX can accommodate either isotropic or anisotropic irradiance distributions (Rich et al. 1994).

### **Total Diffuse Radiation**

The intercepted solar energy that is scattered by the atmosphere, total diffuse radiation, is currently calculated based on an isotropic model, i.e., all sky directions contribute equally to diffuse radiation. This is accomplished by multiplying the skyview factor by a coefficient that converts to units of diffuse radiation flux.

### **Hemispherical Viewsheds**

Hemispherical viewsheds of sky obstructions are calculated by storing the elevation angles calculated when determining skyview factors. These angles can be used to generate hemispherical views upward from a particular surface location and used as input to programs for analysis of hemispherical imagery, for example the analysis program CANOPY (Rich 1989, 1990). CANOPY can calculate a variety of insolation indices, including direct and diffuse site factors (the proportion of direct and diffuse radiation reaching a location, relative to an unobstructed sky) and the duration and timing of direct radiation.

### **MODEL REFINEMENT AND ENHANCEMENT**

It is our intention that the SOLARFLUX model will serve as a prototype for more comprehensive and efficient geometric models of solar radiation. In terms of efficiency, perhaps the greatest advances will be made by implementing optimized subsampling and interpolation techniques that serve in place of the current brute-force method that must perform calculations for every surface location. Three basic extensions of SOLARFLUX are desirable. First, improved atmospheric transmittivity and diffuse submodels, tailored to describe conditions as they change with time and space, could be implemented as user-specifiable mathematical expressions or lookup tables. Second, the ability to account for sky anisotropy could be implemented based on a hemispherical viewshed algorithm (Rich *et al.* 1994). Third, a reflectance submodel, which calculates how surrounding topography affects reflected insolation, could be implemented using viewsheds of terrain (Dubayah and Rich 1995, Rich *et al.* 1994). All of these enhancements could permit incorporation of either theoretical or empirically derived parameter values (Rich *et al.* 1993b).

### **CONCLUSION**

Computer technology has advanced to a level where it is now feasible to model insolation for complex topographic surfaces. SOLARFLUX is a GIS-based model for calculating insolation for topographic surfaces based on first principles, in particular taking into account effects of surface orientation and sky obstruction due to topographic features. The GIS approach offers scale independent simulations and facilitates coupling insolation analysis with other earth system models. SOLARFLUX serves as a useful tool for modeling solar radiation at various spatial scales, and as a prototype for more comprehensive geometric models of solar radiation.

## CHAPTER II: APPLICATIONS

### APPLICATION OF SOLARFLUX AT VARIOUS SPATIAL SCALES

The following are five case studies in which SOLARFLUX is used to model insolation in markedly different systems. Each case study illustrates principles, problems, actual findings, and important implications. The topographic surfaces used for input span scales from tens of kilometers to fractions of a meter — from the landscape level, in which insolation for an entire mountain range is modeled; to the stand level, in which insolation at the surface of a plant canopy is modeled; to the local level, in which insolation for a treefall gap is modeled.

#### LANDSCAPE LEVEL MODELING

##### Case Study 1: Insolation for the Spring Mountains, Nevada

At the landscape level, topographic effects on insolation can define the range of microclimates that serve as the physical determinants of habitat for biological organisms (Weiss *et al.* 1988, Rich and Weiss 1991, Rich *et al.* 1992). In an initial application, we are using insolation calculations to examine the distribution of biophysical determinants of habitat as they influence the distribution and abundance of butterflies in the Spring Range, Nevada, as part of the Nevada Biodiversity Research and Conservation Initiative (Austin and Austin 1980, Saving *et al.* 1994, Weiss *et al.* 1994). An elevation grid was derived from United States Geological Survey (USGS) 1:250,000-scale digital elevation model (DEM) data, at a cell size of 94 m (Saving and Weiss 1994) (Figure 2A,B). Potential clear-sky insolation was then calculated using SOLARFLUX at 30-minute intervals under clear-sky conditions (transmittance 0.6) for three days: the vernal equinox, the summer solstice, and winter solstice (Julian days 81, 172, 355, respectively) (Figure 2C,D,E).

##### Case Study 2: Insolation for Big Creek Reserve, California

In a second application, we are using insolation as a primary driver for a microclimate habitat model that can be used to predict the distribution of vegetation for the University of California Big Creek Reserve (Saving *et al.* 1993). Big Creek, situated in the rugged Santa Lucia Mountains of the central California coast, includes elevations ranging from sea level to 1200 m (4000 ft) with an average slope of 30 degrees (Norris 1985, Saving *et al.* 1993). Because of its topographic diversity, Big Creek comprises a broad range of microclimates, which in turn leads to a high diversity of plant communities, ranging from mesic redwood forest to xeric coastal scrub (Bickford and Rich 1979).

From a vector topographic contour coverage derived by scanning the USGS 1:24,000-scale quad sheets (Figure 3A), we constructed an interpolated surface model using a triangulated irregular network (TIN). An elevation grid was then created from the TIN (Figure 3B). Next SOLARFLUX was used to calculate skyview factors for each location on the surface. Then SOLARFLUX was used to calculate daily direct insolation for Big Creek at 5-minute intervals under clear-sky conditions (transmittance 0.6) for three days: the vernal equinox, the summer solstice, and winter solstice (Julian days 81, 172, 355, respectively). Calculations of skyview factor show the lowest values in the valley bottoms and the highest values on the ridges (Figure 3C). Daily insolation at Big Creek is intermediate at the equinox, highest at the summer solstice, and lowest at the winter solstice (Figure 3D,E,F). Spatial variation is greatest in the winter and lowest in the summer. In

general, insolation is highest on ridge tops and south-facing slopes and lowest in canyon bottoms and on north-facing slopes.

These studies of insolation demonstrate that topography strongly determines microclimate conditions. In turn, plant distributions follow those microclimate gradients. South-facing slopes and ridge tops receive high insolation and thus have higher potential evapotranspiration. Consequently, these regions are drier than north-facing slopes and canyon bottoms, which receive considerably less insolation. Inspection of the vegetation map for Big Creek (Figure 3G) reveals that plant communities adapted to drier, hotter conditions, such as coastal scrub, are found in the localities where insolation is, on average, highest. Where insolation is low for at least part of the year, water availability is higher and communities such as mixed-hardwood predominate. Where insolation is lowest, pure redwood and redwood mixed-hardwood forests occur. Thus topographic heterogeneity leads to a distribution of biotic assemblages that can be predicted on the basis of the effects of insolation on microclimate.

Slope, aspect, and elevation are known by ecologists to have a significant influence on microclimate, however, the importance of sky obstruction by topographic features is less appreciated and was previously difficult to quantify. By calculating hemispherical viewsheds for any location on a topographic surface, it is possible to determine the direction in which the sky is obscured (Figure 4A,B,C). Sky obstruction by topographic features affects both direct and diffuse insolation components. In the case of diffuse insolation, sky obstruction in any sky direction can block insolation from that direction. In the case of direct insolation, sky obstruction along the path of the sun leads to shadows, wherein direct sunlight is blocked during certain times of day. The importance of this process, herein referred to as topographic shadowing, increases with surface complexity.

For complex surfaces, topographic shadowing may be more important than surface orientation in limiting incoming solar radiation. As an example of the importance of topographic shadowing at a landscape scale, we simulated insolation with and without topographic shadowing for Big Creek Reserve (Figure 5A,B,C). An index of topographic shadowing can be calculated as the proportional decrease in solar radiation due to topographic shadowing, i.e., one minus the ratio of insolation calculations with and without topographic shadowing. This topographic shadowing index ranges from zero, with no shadow effect, to one, for a location that is completely in shadow. As would be expected, the topographic shadowing index, based on direct insolation calculations, is highest at the canyon bottoms and on north-facing slopes and lowest on the ridgetops and south-facing slopes (Figure 5D,E,F). Likewise, topographic shadowing is least pronounced at the summer solstice and most pronounced at the winter solstice.

## **STAND LEVEL MODELING**

### **Case Study 3: Insolation for Semiarid Woodlands at Los Alamos National Environmental Research Park**

Study of insolation at the stand level is important because canopy architecture, here defined as the three-dimensional organization of aboveground plant parts, leads to heterogeneity in flux processes involving carbon, heat, and water. For example, in pinyon-juniper woodlands, variation in near-ground solar radiation flux, associated with clumped tree distributions, has a strong influence on water balance (Lin *et al.* 1992), which in turn affects ecological processes at all levels of organization (Martens and Rich *in press*). In a third application, we employ a novel approach whereby we examine insolation as it is modified by plant canopies. This work has been focused at a three-hectare pinyon-juniper



woodland study site at the Los Alamos National Environmental Research Park (TA-51 West) (Rich *et al.* 1993b). In preliminary studies, our approach to modeling insolation has involved three basic steps: 1) mapping and automation of georeferenced locations, stem diameters, and heights of all pinyons and junipers in a three-hectare stand using GIS (ARC/INFO and GRID) (Figure 6A); 2) using GIS to construct a canopy digital elevation model (CDEM) based on the allometry of crown radius to stem diameter and the assumption that tree crown form can be approximated as the upper half of an ellipsoid (Figure 6B); and 3) simulation of intercepted solar radiation using SOLARFLUX (Figure 6C,D,E,F).

Skyview factors were highest on the tops of shrubs and trees and in the center of openings. Overall, the estimated daily insolation was highest at the summer solstice and lowest at the winter solstice. Heterogeneity of insolation was important during all times of year, but most pronounced on the winter solstice, when the south sides of clumps tended to receive the most insolation. For the relatively open, heterogeneous canopies of semiarid woodlands, interactions between canopy architecture and solar radiation lead to heterogeneous microclimates. There is strong differentiation between microsites on different sides of clumps; and sharp microclimate gradients extend from the center of clumps to the center of openings. Thus modeling the explicit geometry of the canopy architecture as it interacts with solar angle permits prediction of the distribution of microclimates as they shift during the day and through the seasons. The ecological implications are important at population, community, and ecosystems scales. We have proposed a "safe microsite model" of community dynamics in semiarid woodlands that would provide a synthesis of the known physiology, demography, water relations, productivity, and nutrient dynamics for pinyon-juniper woodlands (Martens and Rich in press). From the perspective of a seedling pinyon or juniper plant, establishment requires growth in a safe microsite, the distribution and extent of which vary in predictable spatial patterns with climatic fluctuations.

## LOCAL LEVEL MODELING

### Case Study 4: Insolation for Inclined Plots, Waste Cover Design

In a fourth application, we are using SOLARFLUX to examine highly localized patterns of insolation as they affect energy and water balance of waste sites at Los Alamos National Laboratory. In particular, we have examined daily and seasonal patterns of incoming solar radiation on a series of protective barrier plots that range in slope from 0% to 25% while holding aspect constant (azimuth 139°, approximately southeast). Preliminary studies demonstrate that slope orientation (slope and aspect) can lead to significant differences in energy and water balance. Between-slope differences were more pronounced on the winter solstice (Figure 7A) than on the summer solstice (Figure 7B). Even more dramatic differences would be expected for slopes with different aspects.

### Case Study 5: Insolation in Treefall Gaps

In a fifth application, we are using SOLARFLUX to examine highly localized patterns of insolation in forest canopy gaps. Spatial and temporal variation of solar radiation regimes within plant canopy gaps influences energy balance, microclimate, primary production, and water balance. We are conducting a systematic study of the effects of canopy gap geometry on insolation regimes. In particular, we are examining the effects of gap radius, canopy height, and latitude on insolation under clear sky conditions. We are examining insolation for a series of theoretical cylindrical and irregular-shaped gaps across two orders of magnitude of gap radii (1-100 m) and canopy heights (also 1-100 m),

and across latitudes ranging from 0° to 90°. First, we have represented gap geometry by constructing a series of digital elevation models using ARC/INFO GRID. Then, SOLARFLUX is being used to simulate 1) incident direct insolation at five-minute intervals through the day, 2) duration of direct radiation, 3) skyview factor, 4) incident diffuse radiation, and 5) hemispherical viewsheds.

Skyview factors are distributed in a radially symmetrical pattern, with the highest values in the gap center and the lowest values at the gap edges (Figure 8A). Morning shade on east sides of gaps and afternoon shade on west sides of gaps result in pronounced east-west temporal variation of insolation within each day (Figure 8B). Seasonal shifts in solar angle result in pronounced north-south spatial variation of insolation across seasons for all latitudes (Figure 8C,D). For a fixed gap radius, increasing canopy height leads to decreased insolation and decreased spatial variability (Figure 8E,F). The temporal and spatial variation in canopy gaps defines distinct gradients of microclimate, available solar radiation, and water stress, which in turn can affect rates of primary productivity and influence growth and survivorship of plants that become established in a gap.

## CHAPTER III: GUIDE TO OPERATION OF SOLARFLUX

### SOFTWARE AND HARDWARE REQUIREMENTS

SOLARFLUX is based on an ARC/INFO and GRID GIS platform (Environmental Systems Research Institute, Inc., Redlands, CA), running under XWINDOWS on a UNIX workstation. SOLARFLUX has three functional modules: 1) a direct solar radiation module, 2) a diffuse/skyview factor module, and 3) a hemispherical viewshed module. The direct solar radiation module of SOLARFLUX was implemented as set of Arc Macro Language (AML) programs within the GRID GIS environment, while the diffuse/skyview factor and hemispherical viewshed modules were written primarily in the "C" programming language. SOLARFLUX was developed and tested on a SUN SPARCstation running versions 6.1 and 7.0 of ARC/INFO and GRID. The basic functionality of SOLARFLUX requires ARC/INFO version 6.1 or 7.0; however, the hemispherical viewshed and skyview factor modules require the GRID commands *gridfloat* and *floatgrid* functions introduced in ARC/INFO 7.0. Because of the AML implementation, SOLARFLUX is expected to be nearly completely compatible across all computing platforms on which ARC/INFO will run. However, SOLARFLUX is computationally very intensive so a recommended minimum platform is a RISC-based processor workstation. Details of installation are provided in Appendix A.

### PREPARING INPUT DATA — ELEVATION GRIDS

#### Input Format

Elevation data for the surface to be analyzed must be in an ARC/INFO grid format. Due to the elevational compensation of the relative optical air mass, the current version of SOLARFLUX requires the cell size and elevation units in meters. When building the elevation grid, be sure to generate the data at a resolution appropriate for the question being asked.

#### Input Elevation GRID Preparation

Elevation grids can be constructed using a variety of sources: 1) USGS DEMs, 2) contour lines, and 3) other sources (e.g. stereo imagery and survey data).

**Converting USGS DEMs to GRID:** Standard USGS DEM data can be converted to an elevation grid using the ARC/INFO command *demlattice*.

**Generating a GRID From Contour Lines:** Topographic contour lines can be used to build a TIN model using *createtin*. When building a TIN model, the number of flat triangles should be minimized. To display flat triangles, use the *tinerrors* command in ARCPLOT (set the shadeset to colors.shd before using the command). Breaklines along ridge tops and streamless valleys may be useful for correcting errors in the TIN model. A point coverage of known elevations can also be used. With an adequate TIN model, a grid can be generated using the *inlattice* command in ARC. The resolution of the grid should not be smaller than the proximal tolerance of the points, or nodes, in the TIN model. ARC/INFO 7.0 provides a new function *topogrid*, which converts topographic contour lines directly to grids.

## PROGRAM OPERATION

### Starting SOLARFLUX

SOLARFLUX runs within the GIS program GRID. GRID can be started directly from the system prompt using a command line argument:

```
unix% arc grid
```

The following GRID command will invoke the SOLARFLUX menu:

```
GRID: solarflux
```

### Specifying Model Parameters

**Menu control:** SOLARFLUX uses a form menu that provides a convenient interface for specifying model parameters. The user must supply the input surface grid name, the output grid names, day of analysis, start and end times, calculation time increment, global position (latitude and longitude), local time meridian, and atmospheric transmittivity.

**Julian day:** The day for the simulation must be specified in the form menu. The parameter can be entered as Julian day (e.g. 81) or in a month-day format (e.g. 3-22 for March 22). If the parameter is entered in the month-day format, the value is immediately converted to Julian day.

**Start time, end time, and increment:** Start and end times specify the period for which calculations of insolation are to be performed. The time increment specifies the step between each of the series of calculations that are performed between start and end times. Time parameters can be specified as decimal hours, comma delimited, or colon delimited (see example below). Morning or afternoon can be specified with *am* or *pm*. Time parameters may also be entered in solar time (i.e. military time, so 13:00 is 1:00 pm). For example, all of the following inputs represent the same time (1:00 pm): 1:00pm, 1:00p, 13:00, 1,00p, or 13.0. All time parameters are converted to decimal hours and displayed on the input line. In our example, the displayed value would be 13.0.

**Latitude, longitude, and local time meridian:** Latitude and longitude define an approximate global position of the surface. The latitude and longitude coordinates should correspond to a location near the center of the surface being analyzed. The local time meridian is the longitude where the local time zone begins. Specification of longitude and local time meridian is only necessary for situations where it is important to keep track of the time zone. In cases where the user is only interested in solar time, a value of zero should be specified for both the longitude and local time meridian. The surface location parameters may be specified as decimal degrees or comma delimited degrees, minutes, and seconds. As parameters are entered, they are converted and displayed as decimal degrees. For example, 10 deg, 5 min, 2 sec can be entered as 10.5,2 or 10.083888. South and west parameters should be entered as negative numbers. Latitudes must have values between -90 and 90, whereas longitude and local time meridian must have values between -180 and 180.

**Transmittivity:** Surfaces at higher elevations experience greater transmittivity than surfaces at lower elevations due to the shorter attenuation path. SOLARFLUX compensates for elevational effects on transmittivity, so sea-level values should be used when specifying the transmittivity parameter.

**Surface elevation grid:** A display box lists all elevation grids in the current workspace. A grid file may be chosen from the list or specified explicitly by entering the grid file name in the space provided.

**Output Options:** Output options are chosen by clicking the SELECT mouse button on the small raised box near the option title. A check-mark will be displayed in the box if it has been selected. All output options must have a corresponding output grid file name. Three output options can be selected:

**1) total direct with hillshade on:** specifies output of direct insolation that includes the effects of topographic shadowing.

**2) total direct with hillshade off:** specifies output of direct insolation that is based only on surface orientation, i.e. topographic shadowing effects are not included.

**3) duration of direct:** specifies output of the duration of direct insolation in hours.

**Save Parameters:** By choosing the save parameters button with the mouse, the user can save the parameters defined in the menu to a file. The user is prompted for a file name, which should be named with a .sf extension.

**Load Parameters:** By choosing the load parameters button with the mouse, the user can load values stored in a parameter file. A pop-up menu lists all parameter files in the current workspace (indicated with a .sf file extension), and prompts the user for a file name. After the parameters file is loaded, the values are displayed in the menu.

## Running SOLARFLUX

To begin running the SOLARFLUX program, click the Apply button with the mouse. While the program is running, a graphical display shows a hemispherical viewshed of the solar track for each incremental time of simulation.

## Quitting SOLARFLUX

To quit the SOLARFLUX menu without running the program, click the Quit button.

## Running SOLARFLUX in Batch Mode Using Parameter Files

A convenient use of parameter files, besides archiving the simulation parameters, is to run SOLARFLUX in a batch mode. Batch mode operation supplies SOLARFLUX with a list of parameter files, and the program is run for each configuration. Considering the time requirements for typical simulations, the batch mode can be used to run the program through a series of configurations overnight, when computers are typically idle. To use the batch function, generate the parameter files with the SOLARFLUX menu by entering all necessary parameters and clicking the SELECT mouse button on the Save Parameters button. Quit the menu without running the program. Then run SOLARFLUX with a command line argument *file*, followed by a list of the parameter file names. For example, if *file1.sf*, *file2.sf* and *file3.sf* are the parameter files, the command at the GRID prompt would be entered as follows:

GRID: *solarflux file file1.sf file2.sf file3.sf*

## Displaying Output Results

Output grid results can be displayed using standard GRID commands. The following is a summary of some of the useful commands for displaying output grids.

- 1) Describe the output grid to get the value range:

Grid: *describe* <outputgridfile>

- 2) Select an appropriate shadeset:

Grid: *shadeset* <shadesetfile>

For example, use *color.shd* as the <shadesetfile>.

- 3) Use a text editor to create an ASCII look-up table, the left column of which is a range of actual values in the grid, the right column the color value, and with the two columns separated by a ":".

- 4) Set the map extent of the grid:

Grid: *mapextent* <outputgridfile>

- 5) Use gridshade to display the grid file:

Grid: *gridshade* <outputgridfile> # <lookuptablefile>

- 6) The *cellvalue* command can be used to examine values of individual cells within the output grid:

Grid: *cellvalue* <outputgridfile> \*

## Calculating Skyview Factors

To run the skyview factor module, first the user must use ARC/INFO and GRID to prepare elevation, slope, and aspect floating point files. This can be accomplished by the following steps:

- 1) Create an elevation grid, in the same format as for the direct insolation SOLARFLUX module.

- 2) From the elevation grid, produce a slope grid:

Grid: <slopegrid> = *slope*(<elevationgrid>)

- 3) Produce an aspect grid from the elevation grid:

Grid: <aspectgrid> = *aspect*(<elevationgrid>)

4) Convert the elevation, slope, and aspect grids to floating point files (note: the *gridfloat* command requires ARC/INFO v.7.0 or higher):

```
Arc: gridfloat <elevationgrid> <elevationfloatfile>
Arc: gridfloat <slopegrid> <slopefloatfile>
Arc: gridfloat <aspectgrid> <aspectfloatfile>
```

5) Create an ASCII text file, for example *svf\_batch*, containing the following batch process command:

```
svfactor <elevationfloatfile> <slopefloatfile> <aspectfloatfile> <outputfloatfile>
```

6) Run the skyview factor program by invoking the batch process at the UNIX prompt:

```
unix% batch svf_batch
```

Depending on the size of grid files and the computer used, the program can take considerable time to run. For example, a 160KB input grid file running on a 32M RAM SUN SPARCstation 2 requires about 7 hours, whereas a 2.1M grid file requires about 150 hours.

7) Convert the output floating point file to grid file:

```
Arc: floatgrid <outputfloatfile> <outputgrid>
```

### Calculating Hemispherical Viewsheds

To run the hemispherical viewshed module, the user must specify the elevation, slope, and aspect files as floating point input files, along with X and Y grid locations. The following steps produce

1) Create the floating point input files following steps 1-4 in the **Calculating Skyview Factor** section (above).

2) Determine the X,Y position of interest on the input surface. The *GRID cellvalue* command can be used with the mouse to allow interactive examination of a given point's X,Y position:

```
Grid: mapextent <elevationgridfile> *
Grid: image <elevationgridfile>
Grid: cellvalue <elevationgridfile> *
```

3) Run the hemispherical viewshed module:

```
unix% hemiview <elevationfloatfile> <slopefloatfile> <aspectfloatfile>
<xgridlocation> <ygridlocation> <outputfile>
```

4) The output file consists of an ASCII list of sky direction (azimuth angle, zenith) values that connect up to define a hemispherical viewshed.

## Calculating Surface Area Effects

Surface area of the input topographic surface can be calculated as follows, using an AML program developed by Saving and Hetrick (1994):

Grid: `<surfaceareagrid> = sal<elevationgrid>`

The resulting surface area grid can be used to examine incoming solar radiation on a per cell basis, projected in the horizontal plane, as opposed to a flux measurement along the surface itself. This is accomplished by multiplying the surface area grid and the insolation grid of interest:

Grid: `<horizontalfluxgrid> = <surfaceareagrid> * <insolationgrid>`

## IMPORTANT CONSIDERATIONS

### Hard Disk Storage Requirements

SOLARFLUX creates several temporary grids while performing calculations. Adequate space must be available on the hard drive to accommodate the temporary files. After calculations are complete, SOLARFLUX automatically deletes all temporary files. The following methodology can be used to ensure that there is sufficient hard disk space to run SOLARFLUX.

- 1) Determine the size of the input elevation grid:

```
unix% cd <workingdirectory>
unix% ls -l
```

File sizes are displayed in bytes.

- 2) Calculate the disk space (D) required to run SOLARFLUX, based on the number of output options selected (O) and the size of the input elevation grid (I):

$$D = (3 + 2O) I$$

- 3) Determine whether enough disk space is available on the current file system or partition to store the temporary grids:

```
unix% df.
```

The available disk space will be displayed in kilobytes. If using SOLARIS 2.x, use the `-k` switch with this command to display the information in kilobytes:

```
solaris% df -k.
```

Note the period in these commands. This period will cause the `df` command to show the space available on the file system or partition where the coverage exists. Without the period, the command will show the space available on all file systems.



### **Trade-Offs: Input Grid Size, Calculation Period, and Calculation Interval**

Insolation models are inherently calculation intensive. Therefore it is important to consider trade-offs between input elevation grid size, calculation period, and calculation time interval. In particular, simulations involving large grids, long time periods, or small calculation intervals will tend to be slower than smaller grids, shorter time periods, or larger calculation intervals. For example, using a SUN SPARCstation 2 simulations for an input elevation grid of 100 by 600 cells required from 4-6 computing hours to calculate a full day of direct insolation using 30 minute calculation increments, but 8-16 hours using 15 minute calculation increments. It is always important to scale insolation simulations appropriately for the problem being addressed.

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## APPENDIX A: INSTALLING SOLARFLUX

### Installation using FTP

1) Set up and change to the installation directory (this example will show */solarflux* to represent the user-defined installation directory):

```
unix% mkdir /solarflux
unix% cd /solarflux
```

2) Use anonymous FTP via the internet to get copies of the documentation and program files:

```
unix%: ftp glinda.kbs.ukans.edu
      or
unix%: ftp 129.237.122.65

User Name: anonymous
Password: [enter your e-mail address]
ftp> cd pub
ftp> cd solarflux
ftp> get README.solarflux
ftp> bin
ftp> get solarflux.a4.tar
ftp> quit
```

3) Extract the program files:

```
unix%: uncompress solarflux.a4.tar.Z
unix%: tar xvf solarflux.a4.tar.Z
```

### Installation from a UNIX-Formatted Floppy Disk

1) First log in as root or as a superuser:

```
login: root
password: <superuser_password>
or
unix% su
password: <superuser_password>
```

2) Set up the installation directory (this example will show */solarflux* to represent the user-defined installation directory):

```
unix% mkdir /solarflux
```

3) Create a mounting point for the floppy drive file system:

```
unix% mkdir /fd
```

4) Mount the floppy drive device:

```
unix% mount /dev/device /fd
```

For SUN systems, the *device* file is usually */dev/fd0*. Note that *mount /pcfs* will not work for this installation because the *pcfs* mount looks for a DOS formatted disk. The installation disk is a UNIX formatted disk and must be mounted and accessed as a UNIX file system.

5) Copy the program files to the installation directory:

```
unix% cp /fd/solarflux.a4.tar.Z /solarflux
```

6) Untar the program files:

```
unix% cd /solarflux
unix% tar xvf solarflux.a4.tar.Z
```

### Configuring SOLARFLUX

1) Edit *solarflux.aml*. One of the first lines of the program (after some beginning comments) is a variable declaration: *&sv sfpah /dorothy/sf\_a4*. Change the value of the variable to the installation directory: *&sv sfpah /solarflux*. The following are some useful command for the vi text editor that can be used for editing the *solarflux.aml* file:

- **arrow keys** move the cursor.
- **x** deletes the character at the current cursor position.
- **i** enters insert mode.
- **<ESC>** to exit insert mode.
- **:wq** saves and exits.
- **:q!** exits without saving.

2) Copy the edited *solarflux.aml* to the *\$ARCHOME/atools/grid* directory:

```
unix% cp solarflux.aml $ARCHOME/atools/grid
```

### Compiling Skyview Factor and Hemispherical Viewshed Programs

If you wish to run the SKYVIEW and VIEWSHED modules on a UNIX computer other than a SUN workstation, it will probably be necessary to compile the program before it can be run. "C" source code files and compilation instructions are included in the anonymous FTP directory or on the UNIX installation disk. Some compiler-specific changes in the source code may be necessary before the code can be compiled.



## **APPENDIX B: COMMUNICATION CONCERNING BUGS, PROBLEMS, SUGGESTIONS, AND APPLICATIONS**

Please send communications concerning bugs encountered, problems, suggestions for improving SOLARFLUX, descriptions of applications, or other relevant matters to the SOLARFLUX internet e-mail address ([sflux@glinda.kbs.ukans.edu](mailto:sflux@glinda.kbs.ukans.edu)).



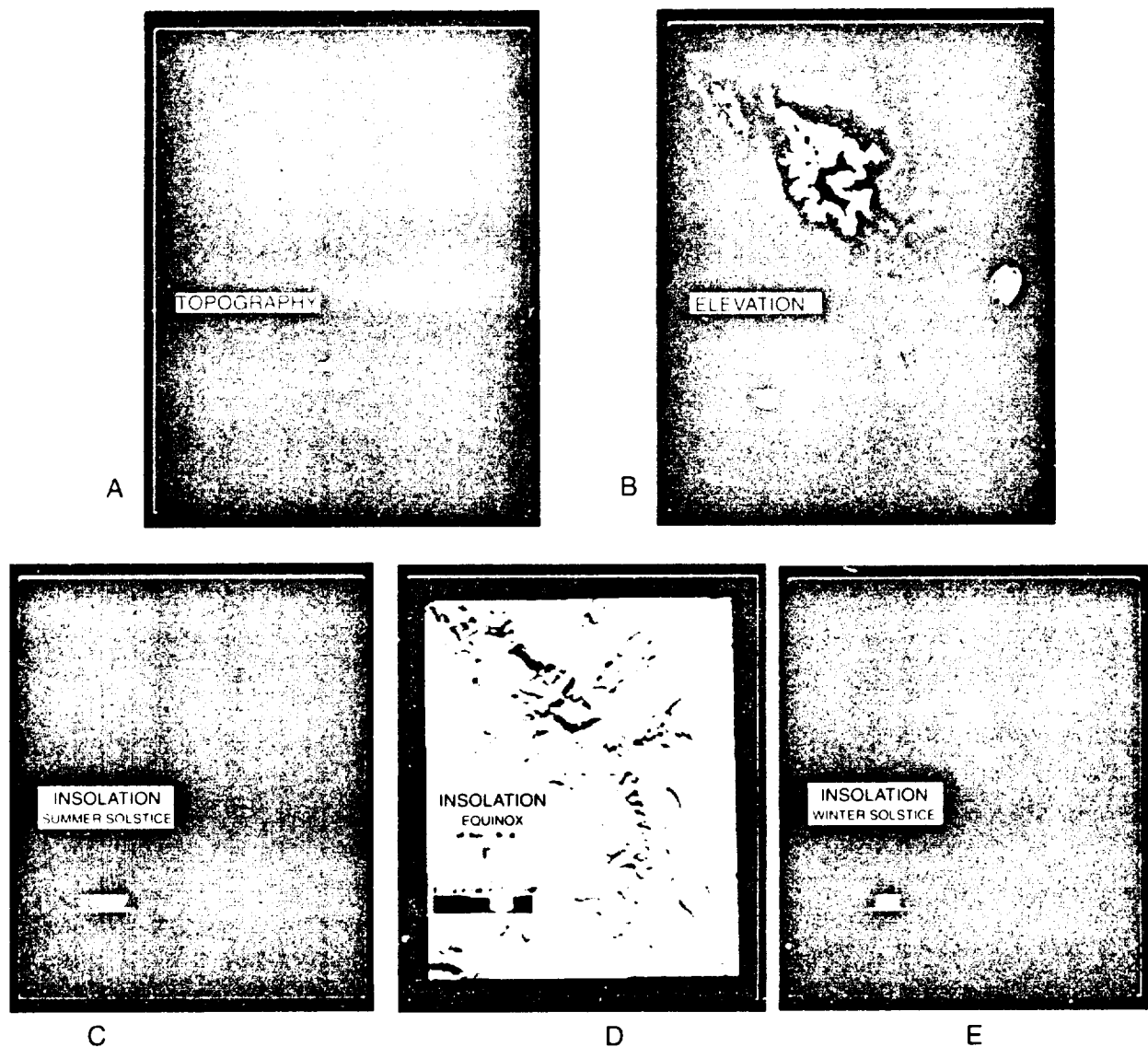


Figure 2. At the regional landscape scale, studies of relations of biophysical determinants of habitat and biodiversity for the Spring Mountains involve A) constructing GIS coverages for topography and butterfly biodiversity sampling sites; B) use of USGS 1:250,000 digital elevation model (DEM) for input to SOLARFLUX; and calculation of daily direct insolation for C) the summer solstice, D) the equinox and E) the winter solstice.

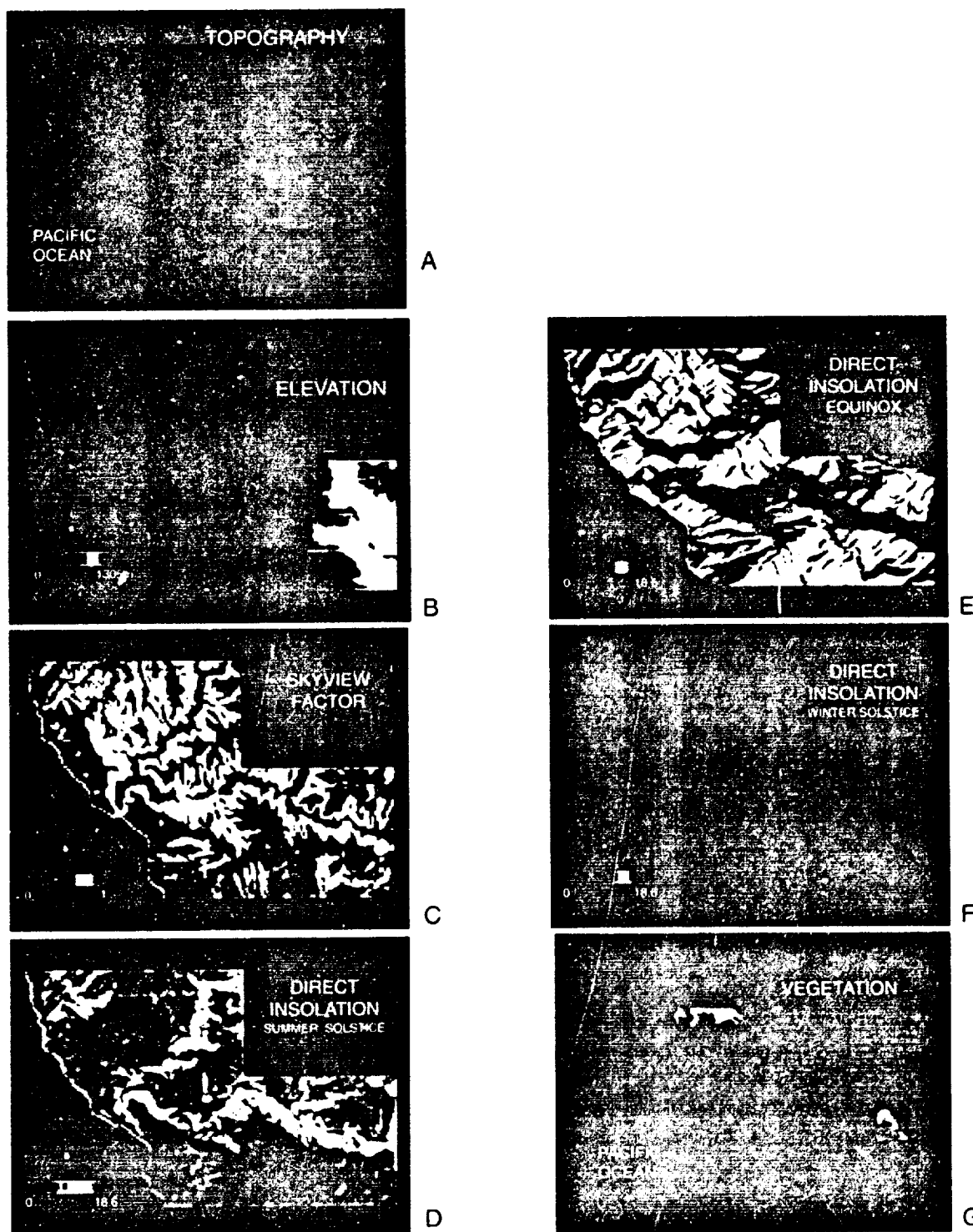


Figure 3. At a more localized landscape scale, construction of microclimate habitat models for the University of California Big Creek Reserve start with A) topography from USGS 1:24,000 quad sheets; next a triangulated irregular network (TIN) model is used to produce B) an elevation grid for input to SOLARFLUX; then SOLARFLUX is used to calculate C) skyview factor; finally SOLARFLUX is used to calculate daily direct insolation for D) the summer solstice, E) the equinox, and F) the winter solstice. There is strong correspondence between topography, solar radiation, and G) the distribution of vegetation at Big Creek.

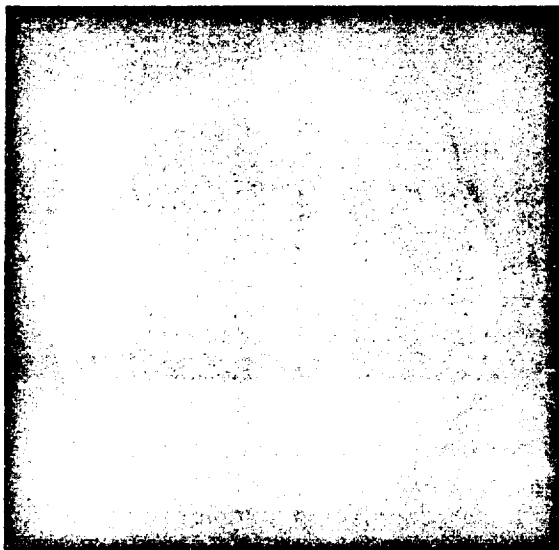
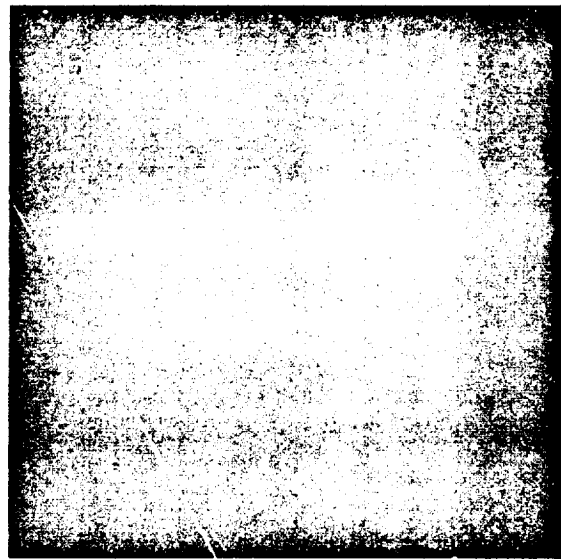
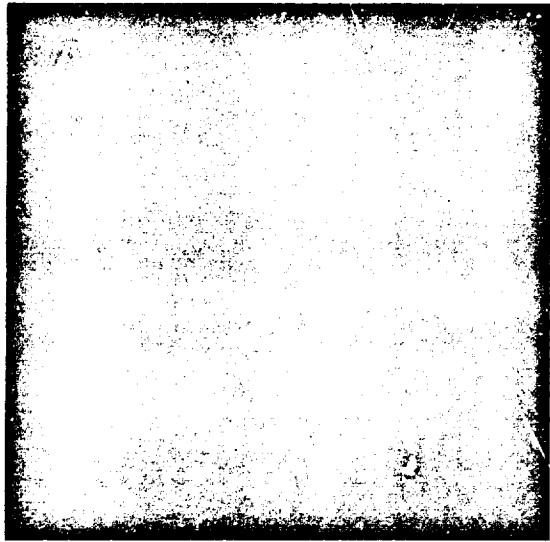


Figure 4. Hemispherical view sheds, calculated for locations corresponding to the A) low, B) mid, and C) high elevation weather stations at Big Creek, show sky directions that are obscured by surrounding topographic features.

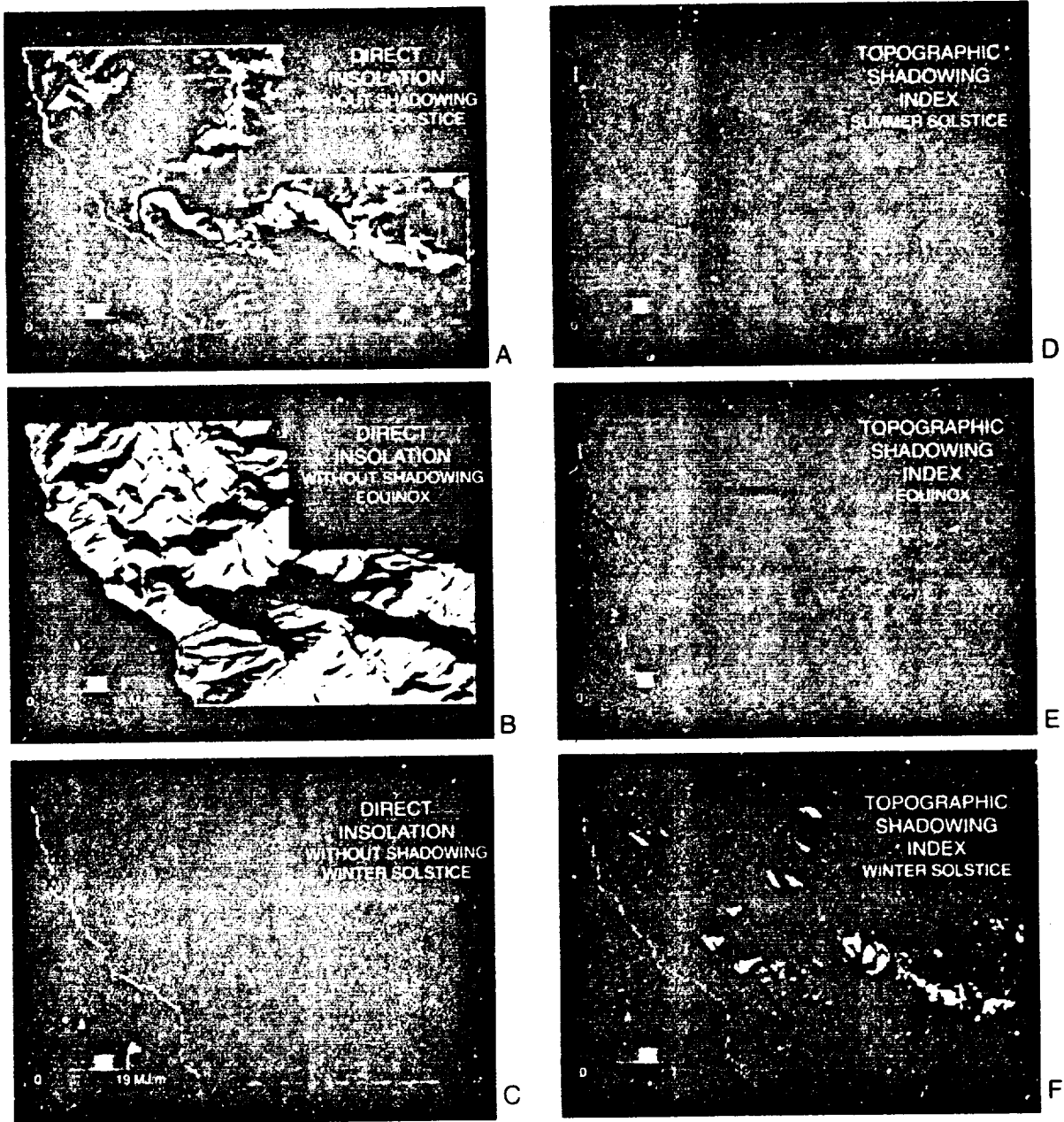


Figure 5. An index of topographic shadowing for Big Creek Reserve can be constructed by calculating daily direct insolation with shadow effects taken into account (see figure 3) and daily direct insolation without shadow effects taken into account for A) the summer solstice, B) the equinox, and C) the winter solstice. The index, calculated as one minus the ratio of radiation values without topographic shadows and the values without topographic shadows, serves to show the proportional decrease in direct radiation due to shadows for (D) the summer solstice, E) the equinox, and F) the winter solstice. Note that a topographic index value of 0 indicates no shadow effect and a value of 1 indicates a 100% reduction in direct insolation due to shadows. Gray areas signify undefined topographic indices, resulting for locations always in the shadow of their own slope.

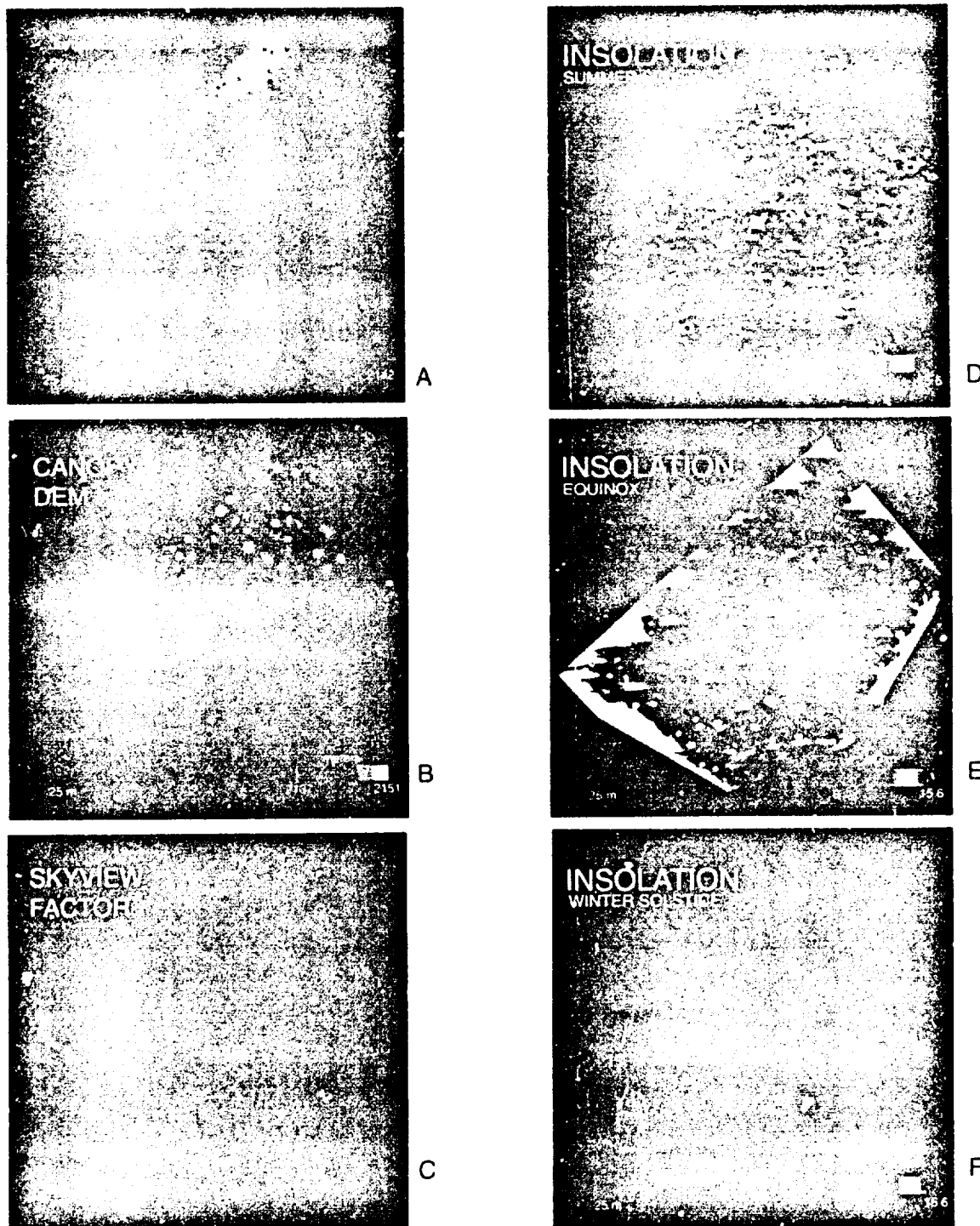


Figure 6. At the stand scale, studies of influences of canopy surface topography in pinyon-juniper woodlands at Los Alamos National Environmental Research Park involve A) mapping all tree and shrub locations; B) construction of a canopy digital elevation model (CDEM) based on the height and crown radius of each tree and shrub, with the assumption that a hemiellipse approximates the outer envelope of the canopy surface; use of SOLARFLUX to calculate C) skyview factor; and use of SOLARFLUX to calculate daily direct insolation for D) the summer solstice, E) the equinox, and F) the winter solstice.

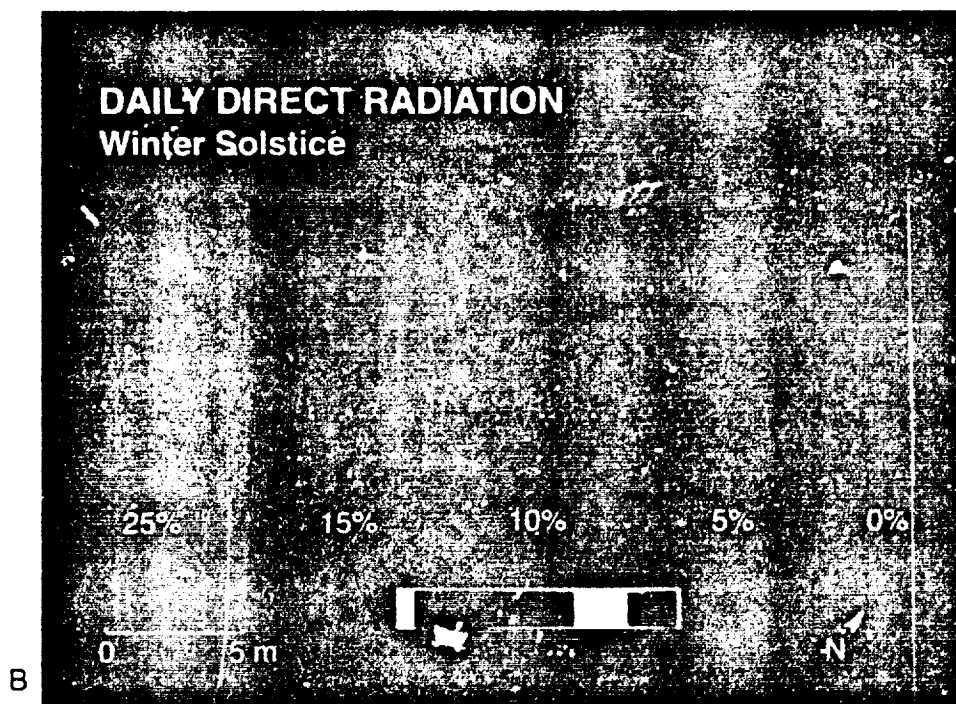
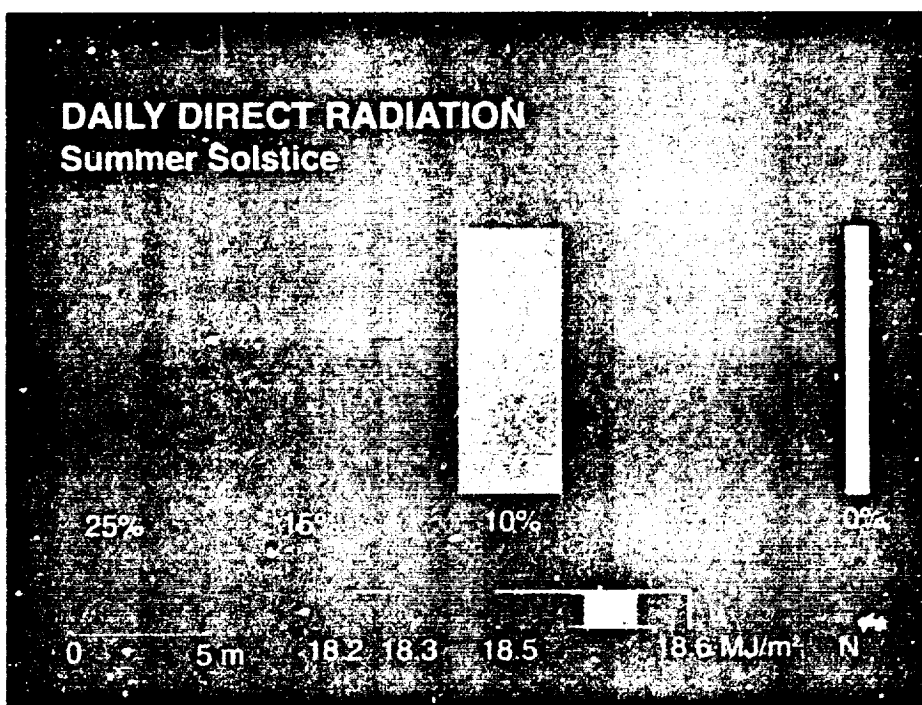


Figure 7. At the local scale, daily direct insolation was calculated using SOLARFLUX for A) the summer solstice, and B) the winter solstice for a series of demonstration plots, being used to evaluate the influences of slope on water balance in waste sites. All plots are oriented toward a southeasterly aspect and slope varies from 0% to 25%.



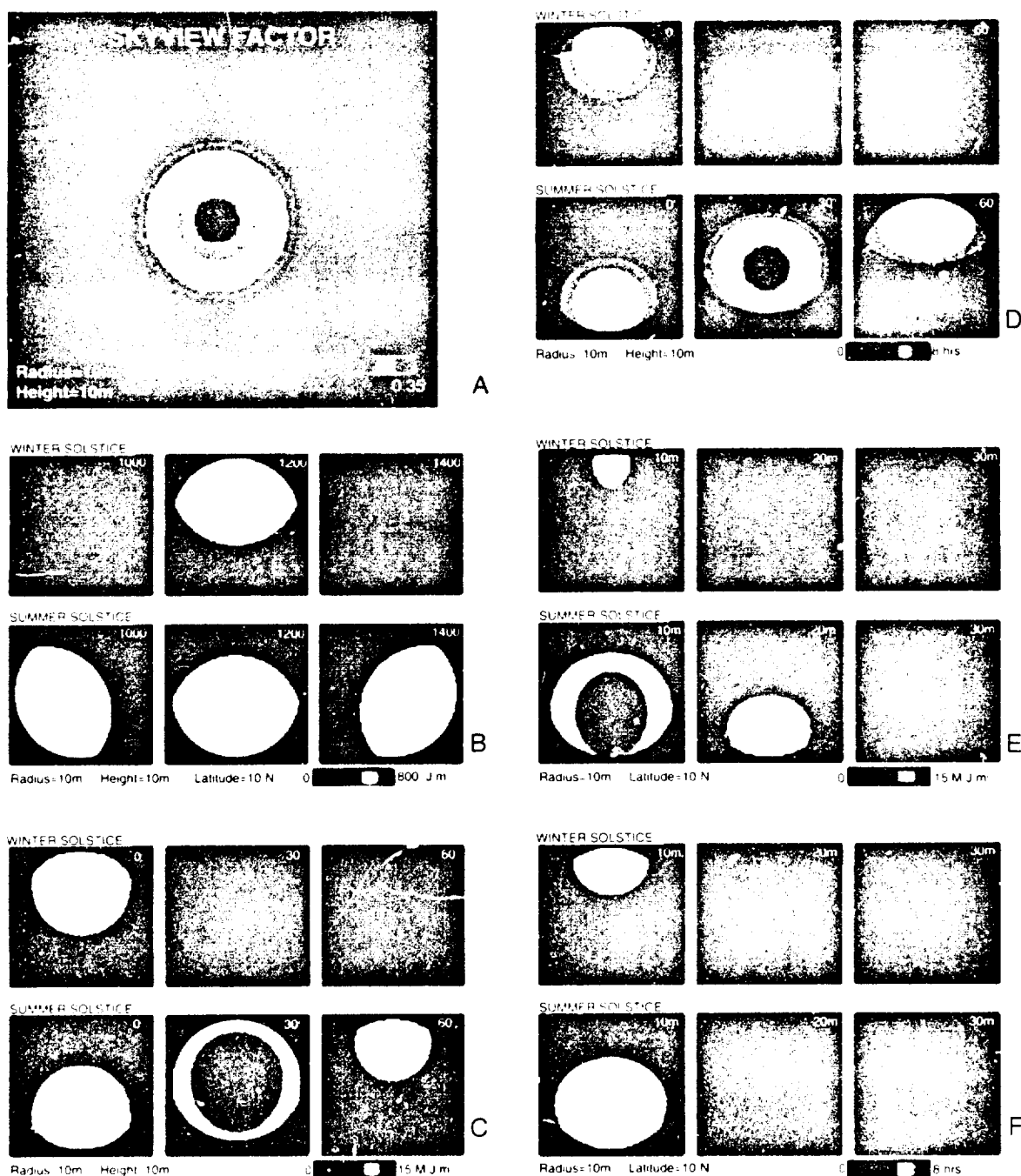


Figure 8. SOLARFLUX calculations of spatial and temporal insolation variation for a series of simulated forest canopy gaps. A) Skyview factors are distributed in a radially symmetrical pattern. B) Instantaneous direct insolation depends upon time of day and time of year. Effects of latitude on spatial and temporal insolation variation are shown in terms of C) daily direct radiation. Similarly, effects of relative gap size are shown by increasing canopy height, while holding gap size constant, in terms of E) daily direct radiation, and F) hours of direct radiation.

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